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HUMAN EXPOSURE TO ELECTROMAGNETIC FIELDS FROM MOBILE PHONES

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Abstract. A mobile phone can emit a few watt power in the vicinity of the human head. The paper reviews the different types of the mobile phones, the related exposures, the assumed biological effects as well as the health safety recommendations and test methods. An isotropic $E-$field probe suitable for phantom measurement is also described.

Key words: Mobile phones, human exposure to electromagnetic fields, safety recommendations, phantom measurements, $E-$field probe.

1. Introduction

The mobile telecommunication market is evolving very quickly and a huge amount of people is involved. Due to the quick changes the statistical information can not be update. The consolidated statistics from 1996 show that the number of CMP users increased by 10-30 % between January and June in the different European countries. The situation can be characterised by the penetration, which is the ratio of the CMP subscribers in the whole population. In Scandinavian countries this parameter now is about 50 % and is still growing. In Hungary the 10 % was exceeded in October 1998. The growing rates are the greatest in countries like East Europe, where the public phone service is insufficient. However the saturation level is not prognosticable yet. May be that in the future everybody will have a mobile phone, some of them two one business and one private which will provide the services without restriction in space and time. The wire communications as the public phone remain mostly for data transfer. Therefore the study of

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the possible related health risks is important for the safeguarding the public health.

Because there are practically no natural background of the radio frequency radiation as an opposition to the nuclear radiation it is difficult to forecast the possible biological effects. There are general fears - sometimes even hysteria - in the society from these effects. At the same time the benefits can not be ignored and the mobile telecommunications, above all the cellular phone systems increase with an astonishing extent. The science is liable for the correct investigations of the possible biological effects. The base of the investigations is the precise dosimetry.

In this paper the sources of the electromagnetic fields connected with the mobile telecommunication are outlined at first, than the possible biological effects and the safety recommendations will be listed. Finally the key device of the test measurements, the $E-$field probe will be described and characterised.

2. Sources

The mobile telecommunication devices can be divided into main categories, depending on the network they use. Such a possible taxonomy is the following:

1. Private/Professional Mobile Radio (PMR). These systems sometimes are called "professional" mobile radio, they are used to provide an internal communication network within a fleet of vehicles or individuals using portable and/or hand-held units (walkie- talkies). In many cases the transmitter is a potable unit, hanging on the belt of the user and the phone is connected to it with wires.

Examples are: taxi and ambulance companies, security and firemen divisions, etc. In some network the mobile units communicate via one, or several base stations, in some other networks there are no base stations and the mobiles communicate directly with one another. The communication is possible only among the members, There is no direct access to other telephone networks. In some networks data transmission is also possible. The networks in which only data services are possible are also called Wide Area Networks (WAN) marking it off from the Local Area Networks.

2. Radio Local Area Network (RLAN). These systems allow the data transfer between computers within a limited territory, e.g. in a building or campus. The Local Area Network (LAN) is built usually from wire connections, but nowadays some new system use radio connections for simplifying the installation and allowing the portability of the units. These network

are called Radio Local Area Network (RLAN), or Wireless Area Network (WLAN). These networks use no hand-held phones, only portable, or permanently installed transmitters.

3. Cordless telephones (CT). The CT provides a short range radio connection between the hand-held unit and the fixed public telephone unit. The first generations utilised simple analogue modulation and sometimes occurred disturbing interference with other CTs and even with other electronic equipment (TV, computer, etc.). The new generations are digital, their working principle is very close to the cellular phones, but with reduced performances for lower cost. Many of them offer connection between more mobile units too. In some systems the data transfer is also possible. The service area is small, it covers usually only a home, the maximum range is in the great of order of hundred meters. This applications generally use low powers.

4. Cellular Mobile Phone (CMP). The cellular radio systems apply full duplex (transmit/receive capability in separate radio channels) communication between the hand-held phones, or units mounted on vehicles to fixed base stations. The coverage of the base station is called as a cell. The typical range of the cell is between 0.5-15 km, the maximal extension is about 35 km. The base stations are also interconnected with microwave links ensuring the communication between hand-held phones within the full network, further interconnection to public telephone networks and other cellular networks are possible.

From the early 1980s different analogue cellular networks have been built in the North America and in Europe. Their working frequency bands are around 150, 200, 450 and 900 MHz. In 1992 a new digital system were established. This apply the harmonised European standard GSM (Global Signal Management). The digital systems offer much better performance and spectrum efficiency compared to the analogue ones, the data transfer is also provided (Fax and computer). In the latest years The DCS 1800 system has been introduced. Its characteristics are very similar to the GSM except that it operates at 1.8 GHz and not at 900 MHz. The number of subscribers increase rapidly which results in the more dense settlement of base stations especially in the cities. The decrement of the cell size reduces the output power of the hand-held devices.

In other parts of the world other digital systems are used, with similar properties. E.g. in Japan the PDC, in the USA the PCS are used. The NADC systems are popular in North America, in Asia, in the Pacific region as well as in Russia and in Israel.

5. Flight Telephone (FP). This systems provide communication (voice

and data) for the passengers of commercial flights, where the use of the cellular phones are forbidden due to safety recommendations (not to interfere with the plane electronic systems). The FPs are specially deigned from an electromagnetic compatibility point of view. The passenger uses a wire phone and the radio equipment is mounted on the plain, it communicates with ground stations that provide the interconnection to other telephone networks as public network, different CMP networks or even satellite network.

6. Satellite Systems (SS). Satellite systems are in principle cellular systems, except that the base stations are not on the ground but on the board of satellites. Compared to the land networks, satellite systems offer a greater coverage but with a lower capacity. They are aimed to be complementary with the land networks by enabling communications from remote locations (sea, desert, mountains) or from areas with low population density where the building and maintaining of the cellular land network would not be economical. The first systems were set up for the need of the mariners. The International maritime satellite organisation (Inmarsat) operates the network involving 4 geostationnary satellites (at an altitude of 35800 km) that cover the world, except the poles. The permanently installed units mounted on the boards of ships and on ground locations communicate to the satellites with parabola antennas. Four different standard (Inmarsat A, B, C and M) were developed for different applications.

The newest systems aim the use of the hand-held units - very similar to the CMP - for satellite systems. The firs one, which is already in work is the Iridium, which covers the whole world with 66 base stations placed on the board of low earth orbit (at an altitude of 780 km) satellites. Two further similar systems with smaller coverage are under development: the Globalstar (48 satellites) and the Ellipso (14 satellites). Networks based on medium and geosynchronous earth-orbits are also under development (ICO, Inmarsat P, Asian Cellular System, Thuraya).

The Table 1 summarises the emission characteristics of the different sources. The continuos and pulsed EMFs can have different biological effects, therefore this characteristics are also summarised in the table.

3. Exposure

The permanently installed sources do not give rise to remarkably exposure if the installation is correct. The portable units can be placed distant from vital organs for decreasing the exposure. These devices can be treated according to the safeguarding regulations similar to other high-frequency instruments. In contrary the hand-held phones are hold in contact with the head during work. As it can be seen in the Table I the rms emitted power of

Table 1. The sources of electromagnetic filds
in the mobile telecommunication tehniques.

Category	Systems	Unit type[1]	Frequency $(MHz)^2$	Power $(W)^3$	Pul sed
PMR	ARDIS	P	806-824	40	–
	COGNITOR	P	176-191	5	–
	DATATAC	P	400-900	4-20	–
	MOBITEX	P	80-900[4]	2-20	–
	EDACS	P/Hh	80-900[4]	10/5	–
	MPT1327	P/Hh	50-500[4]	10/5	–
	ETSTPMR	P	30-10[4]	n.a.	–
	CDPD	P	835	n.a.	+
	TETRA	P/Hh	380	2.5	+
RLAN	Many different	P_i/P	915	1 0.025	+
	ALTAIRPLUS II	P_i/P	18500	$0.1-1$	–
	WLAN	P_i/P	2450		–
CT analogue	CT0	Hh	40	0.01	–
	CT1, CT1+	Hh	900	0.01	–
	JCT	Hh	$250-380^4$	n.a.	–
CT digital	CT2, CT+	Hh	850–900	0.0	+
	DECT	Hh	1900	0.5	+
	PHS	Hh	1900	0.01	+
CMP analogue	TACS	P/Hh	900	1.6/6	–
	ETACS	P/Hh	900	10/1.6	–
	RADIOCOM	P	$165-900^4$	11	–
	NMT 450	P/Hh	450	15/1.5	–
	NMT 900	P/Hh	900	6/1	–
	AMPS	P/Hh	840	3/0.8	–
CMP digital	PDC	P/Hh	$810-1500^4$	1/0.2	+
	GSM	P/Hh	900	1/0.25	+
	DCS	Hh	1750	1.125	+
	NADC	P/Hh	835	3/0.2	+
	NADC IS95	P/Hh	835	6.3/0.2	–
	PCS	P/Hh	1900	/0.125	+

[1] P: Portable; Hh: hand-held; Pi: Permanent installed.
[2] The frequency values in the table are the rounded values of the centre of the uplink band.
[3] The maximum rms output powers as regard to the different type of units.
[4] Diferent bands in the frequency region depending on the country.
[5] Peak powers, depending on the system.

Table 1. continue.

Category	Systems	Unit type[1]	Frequency $(MHz)^2$	Power $(W)^3$	Pulsed
FP	TFTS	P_i/P	1670	0.5	+
	IMARSAT- -AERO	P_i/P	1640	5 $20 - 350$	+
SS existing	IMARSAT A, B, C and M	P_i/P	1644	$10 - 4k^5$	+
	IRIDIUM	P/Hh	1618	0.338	+
future	GLOBALSTAR	P/Hh	1618	5/1	−

the earlier generation analogue hand-held units are in the great of order of watts, while in the case of the new digital phones this value decrease below 0.5 W. However it should be noted that most of the digital units emit pulsed power. The reason is that the digital systems allows several users to share one channel simultaneously. Different access techniques are used. The main principal ones are:

- Frequency Division Multiple Access (FDMA), each channel is divided into sub-channels;
- Code Division Multiple Access (CDMA), the signals from several users are encrypted all together and transmitted on one channel. In the receivers decryption filters are used;
- Time Division Multiple Access (TDMA), in this case one user communicate during a small portion of the time only, the second one during the next portion, and so on. For example in the GSM system 8 users share the time. Voice is encrypted and the digital file is compacted for transmission. At the receiver the inverse process ensures for the listener the sensible continuos conversation.

The digital cellular mobile phone systems use the combination of these techniques: the GSM, PDC, DCS 1800 and NADC apply the FDMA/TDMA method. That means that the primary channel distribution is according to frequencies separated from each other by 200 kHz, and in each frequency band TDMA provides the shared use of several users. Therefore the output power of the phone is pulsed. In the case of GSM and DCS 1800 systems 8 conversation can continued at each frequency. The duration of the pulses is 0.577 ms, the repetition frequency is 217 Hz. The peak value of the power is 2 W for the GSM and 1 W for the DCS systems.

The GSM phones always emit the maximum power for a few seconds during building up the connection with the base station. Therefore people having electronic implants should not hold the phone in its vicinity (e.g. in the upper pocket of the coat if they have pacemaker) for avoiding the electromagnetic interference. It should be noted here, that user does not know when the connection is building up. The phones send registering signals to the nearest base station in each 5-10 minutes. Also the ringing starts only after the connection has been built. During the conversation the power is usually smaller than the maximum, the output power of the phone is regulated down to the level which is just enough for the safe connection. The exception is the case when the base station is very far ($\simeq 15\ km$). In cities and densely populated areas, where many subscribers live the cell sizes are smaller (even in the range of $100\ m$) which makes possible the multiple use of the frequency bands. In the territory of a great town each frequency is used 20-30 times in second neighbouring cells.

4. Biological Effects

The research of the interaction of the electromagnetic fields and biological organs have been in progress since long. As an accompanying of the development of the electrical industry the effect of the $50\ Hz$ magnetic fields were investigated. From the advent of the radar the potential interactions of radio frequency fields with the human organ have been searched. Now as the personal radio telecommunication is spreading this works have been proliferated. The biological researches cover the theoretical studies of the possible mechanisms of interaction, the experimental and numerical dosimetry, in vitro investigations of different cell cultures, animal and human researches and even epidemiological surveys.

In general the RF fields occur heating. The radio frequency quantums excite the rotations of the water molecule and some organic molecules too. Due to collisions the rotation energy of the molecules converts to disordered thermal motion and the temperature will increase. The problem is that different biological and even psychical effects were observed at very low doses, when the temperature rise was negligible. Therefore the effects are divided into two categories:

- thermal effects, if the dose occurs at least $0.1K$ temperature increment;
- non-thermal effects for more lower doses.

The possible mechanisms of the non-thermal effects are the key question. The RF frequencies are more greater than the frequency of any biological process. Therefore the low- frequency modulation of the carrier can have importance. Some biological effects were also different under CW and pulsed ("GSM like") $900\ MHz$ fields. The possible explanation is the demodulation of the signal by the rectifying characteristics of the cell membranes. The experiments contradict to this theory [1]. Motor neurones and muscle tissues were stimulated by pulsed sine waves under in vivo conditions. The biological effect was detected if the carrier sine wave was 10 kHz. As the frequency of the sine wave increased up to a few MHz the response decreased, at 900 MHz and at 1.8 GHz the effect did not exist. The cell membrane "diode" seems to have a very low cut-off frequency as it can be expected. This experiment does not support the idea that the pulsed RF fields from the mobile phones occur any changes in the biopotentials, only the heating exist unambiguously. The question whether the pulsed heating occur different effect compared to the continuos is still open. The general problem with the mechanisms of the low-energy heating effects is the lack of the generally accepted thermal model of the living organs.

Many different psychological effects were also observed under low-dose conditions. Even the changes in the electro-encephalograph (EEG) curves of rats and also for humans were reported [2]. This effects exist under the exposure to the RF field and diminish within a time of about half an hour after switching off the radiation. Phone users questioned in surveys reported on headache, troubles in seeing and hearing, etc. These complaints have not found to be correlated with statistical significance to the electromagnetic field of the mobile phones.

The newest laboratory investigations show that the reaction time is influenced [3]. In the experiments the subjects were exposed to 915 MHz continuos and GSM like signals (modulated by 217 Hz pulses with 1:8 duty cycle), the mean power was 1 W. The cerebral blood flow was also logged by ultrasonic method. The simultaneously fulfilled psychological tests improved an increase in the responsiveness, namely the choice reaction time. The effect was stronger in the case of continuos and less for the GSM like fields. This could be associated with the mild localised heating of a specific area of the brain. The ultrasonic blood flow measurements also showed some evidence to a very small temperature increase. However the authors do not exclude the possibility of the non-thermal effect.

It should be clearly stated here that there is no any evidence on permanent health damage in the non-thermal region. The relatively weak effects diminish after switching off the exposure. The thermal effects are more evident, an overheating to 43°C kills rapidly the cells of mammals. The overheating of the eyes occur eye greying, which is know among workers in worm workshops.

The main fear of electromagnetic fields is the possible risk of cancer. Many surveys have been made even in occupational groups exposed to RF at work (radio and radar stations) but up to now no reproducible significant effect was reported. It should be noted here that the 50 Hz fields have fold under the same suspicion many decades ago. This frequency is not very far from the speed of biological processes. The surveys regarding the 50 Hz fields were made on much numerous groups and longer than it was possible to do it on the RF exposed people. Significant effect was not reported for a long time. However in 1998, after the last 9 year long systematic research projects the exposure to power-line frequency was declared as a "possible" human carcinogen [4].

5. Limitations and Test Methods

No internationally accepted standards exist for the limitations of the magnitude of the field around the mobile phones. In Europe the CENELEC (European Committee for Electrotechnical Standardization) worked out recommendations, this is treated as European "pre-standard". In the US the IEEE published similar recommendations. Both papers start out from the heating effect and they limit the power absorbed in the body of the user (SAR). In general the allowed limits of the absorbed RF power start out from the value of 4 W/kg. This value origins in the animal experiments, namely if the experimental animals (rats) suffer a full body exposure of 4 W/kg then their behaviour changes (e.g. they will not eat even if they are hunger). The behavioural change elapse after a short recovery period when the exposure is finished. This irradiation should occur a temperature increase for humans if the exposure time is long enough. In the course of a 24 hours exposure the 4 W/kg would mean about 5000 kcal energy absorption for a human weighted 60 kg. Therefore the international committees proposed the one tenth part of the above value as the absolute limit of the a absorbed RF power regarding the full body. The 0.4 W/kg is the generally accepted limit for the full body exposure for occupational. For the general public only one fifth part is accepted, i.e. 0.08 W/kg. It should be noted that this values are often debated [5], because sometimes behavioural changes of the experimental animals are found even at 0.5 W/kg exposure. It is not clear to what extent is responsible the heating of the thermoregulatory system controlled by the central nervous system for these effects. Because the RF power absorbs strongly in the living organ, the field decreases very quickly within the body. It decreases a great of order within 1-2 cm. Therefore the exposure of the brain area differs for small animals and for humans. As a first principle the animal studies can be considered as a safe worst case for human.

If only a part of the body is exposed then the above limits can be increased because the blood circulation effectively thermalizes the exposed organ. The exception are the eyes and the testicles in which the density of the blood vessels are small, therefore these organs can overheat more easy than the other parts of the body. As a final conclusion of the above considerations the CENELEC recommendations tell the basic restrictions which are listed in Table 2.

Table 2. The basic limits of the specific absorbed power (SAR) acording to the european pre-standard env 50166-2.

	SAR averaged over the whole body	SAR in organs other than hands, wrists, feet and ankles averaged in any 10 g tissue	SAR in hands, wrists, feet and ankles averaged in any 10 g tissue
General Population	0.08 W/kg	2 W/kg	4 W/kg
Workers	0.4 W/kg	10 W/kg	20 W/kg

Notes: The above SAR values means the average over any 6 minutes time interval. The averaging mass has chosen as a cube.

The IEEE regulations are a bit more rigorous. For the case of mobile phones only 1.6 W/kg instead of 2 W/kg is allowed and the mass-averaging is limited to any 1 g tissue. Due to the strongly decaying distribution of the RF power the IEEE regulations can be estimated to be three times more strict than the Europeans one.

The main technical problem with this prescriptions are that the absorbed energy can not be measured directly. The safety check needs indirect physical, or numerical methods. The investigations are performed on phantoms having the shape and dielectric properties as close as possible to the human. The dielectric properties (dielectric constant and conductivity) of the different human tissues at these frequencies are known [6]. In numeric computation methods [7] the phantom can have a detailed match to the human body; the usual mesh sizes are 5 mm. The models for the phone antenna are not so exact. Monopole antenna models are used with typically overestimated ground planes, e.g. the mobile box is treated as conductive earth plane. The simplest physical phantom is a head form from thin plastic or glass shell filled with a liquid having the same dielectric properties as the brain. More sophisticated phantoms composed from different materials for bones, skin, eyes etc. are also in use [8]. The limitation of physical phantoms is that they should be suitable for the penetration and moving of a probe.

Robot systems which moves the probes in the phantoms and computes the distribution of the electromagnetic power are commercially available [9].

A numerical model computations [10] show that the half or more of the emitted power absorbs in the head. The supposed output power of the phones was 0.6 W and the obtained maximum SAR values for the different phone models were between 2-3.5 W/kg if the averaging mass was 1 g (IEEE recommendations) and between 1-2 W/kg if the averaging mass was 10 g (CENELEC recommendations). The bio-heat model developed by the same authors [11] resulted the maximum temperature increase in the ear-lobe region, its value lies between 0.22°C and 0.43°C. In the brain region the maximum temperature increase is only in the range of 0.09-0.16°C . In the case of the GSM systems the maximum of the rms. output power is only 0.25 W, so the above values should be decreased proportionally.

The above and similar investigations confirm that most of the phones fulfil the requirements of the mentioned recommendations however not with a great safety factor. Therefore the careful check of the different types of mobile phone units is necessary. The test method should ensure that the resulted SAR values do not underestimate the real exposure of a realistic group of users, including children of three year and older. The manufacturing tolerances should be taken also into account. The tests should be made at the greatest power. The intended use should be modelled including both right-hand and left-hand operation. The simulation of the upper body is required (head-shoulder phantom), but the simulation of the hand is not necessary. The 10 g averaging mass should fill out a cubic volume, etc. The detailed description of the requirements are given in [12].

Devices with output power equal, or less than 20 mW (most of the cordless phones) satisfy the required limitation. I.e. under the worst case conditions if the whole emitted power is absorbed by the users head and it is concentrated into a small volume then the SAR maximum will be 2 W/kg integrated over 10 g mass.

It should be noted also here an other measuring method. According to [13] the SAR value induced at the surface of a biological body can be approximated from the tangential component of the incident magnetic field. The incident field is the field strength at the same location relative to the source without the presence of the body. This approximation has been tested in the frequency range of 300 MHz to 2 GHz and found to be accurate within ± 3 dB. Because the SAR is the greatest at the surface this value always overestimate the average in the cubic volume of the 10 g mass. The CENELEC recommendations also accepts this measuring method, but gives an additional 3 dB factor (altogether 6 dB) in order to account for further uncertainties. As we have seen above the recommended limits are too close to the real exposure values. Therefore the declared uncertainties of this method are too great for accurate test measurements.

The key device of the experimental test measurements is the probe, which measures the absorbed power. In principle the probe can sense the temperature increase, but thermistor probes have low sensitivity. Under laboratory conditions this problem could be solved by power enhancement, but it results in the overheating of the phantom material, turbulence occur and the accuracy decreases. The thermal probes are mainly used for calibration purposes only. In practical tests the $E-$field, or $H-$field probes are used. The $E-$field probes are the simpler, because they can be constructed from short dipole instead of coils.

6. The E-Field Probe

Because the biological tissues are non-magnetic materials, the absorbed power is equal with the Joule heat of the induced current:

$$SAR = \frac{\sigma}{\rho} E^2 \tag{1}$$

where SAR is the specific absorption rate in units of W/kg, σ, ρ and E are the electrical conductivity, the mass density and the value of the electric field respectively.

The field measuring probe should met to the following requirements:

- isotropic reception, i.e. the sensitivity should not depend on the polarisation of the field;
- small size, ensuring good resolution in space;
- the scattering of the field from the probe and the connecting wires etc. should keep as small as possible;
- minimal perturbation of the dielectric structure of the phantom.

The realisation of such probes consist of three mutually orthogonal short dipole antennas mounted with detector diodes in the gaps and connected to the amplifier with high resistive leads. Fig.1. shows several different possible arrangement of the dipoles [14].

Most probes apply the triangular arrangement because its symmetry. The common feature of these probes is that the structure is fabricated on a dielectric substrate and an outer plastic cover prevents from the penetration of the phantom material. As in the course of the measurement the probe is immersed in the phantom and moved in it, it results in a continuous

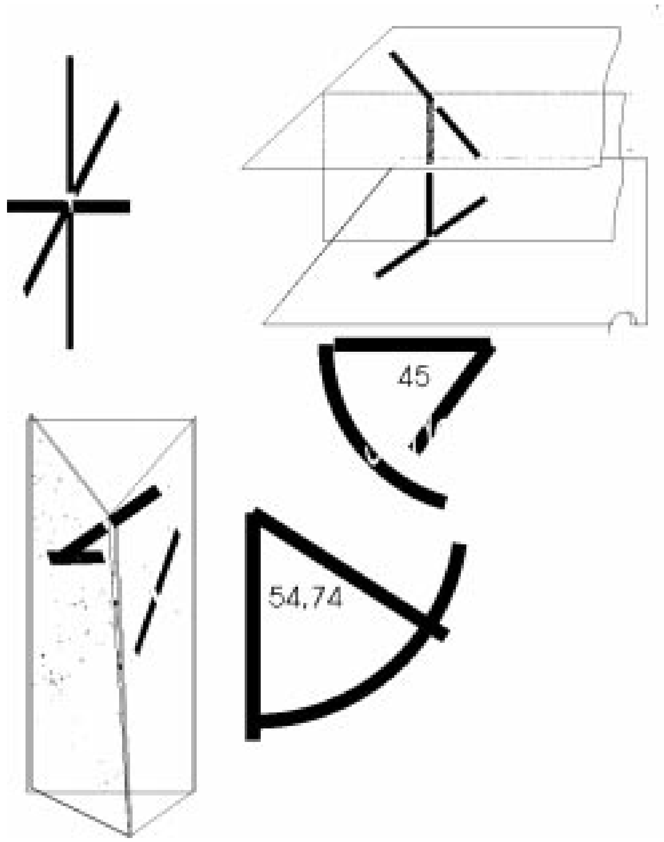

Fig. 1. Posible isotropic arrangements.

rearrangement of the phantom material even in the close vicinity of the sensing elements. This artefact can make uncertain the measured results in a complicate structured phantom where resonance can occur. In this work an other construction is reviewed, where the sensing structures are made on very thin substrate and are isolated by thin foils; the phantom liquid surrounds them, so the redistribution of the phantom-model is minimised [15].

The probe is fabricated by thick film technology on 125 μm thick polyester substrate. The conductive parts are screen-printed: the dipoles from silver paste, the resistive lines from carbon paste. The detectors are zero bias diodes. Two different measures have been realised; the dimensions are shown in Table III.

Isolating lack and thin foil covers the printed circuits. Three individual parts are placed together at the long edges forming a cross section of a

Table 3. The main dimensions of the probe.

Domension in mm	Probe 1	Probe 2
Probe width	7	4.5
Probe length	315	342
H	2.5	1.6
D	2	1.5

The H and D means the half-lenght of the dipoles and the distance between the two resistive lines respectively.

regular triangle. This construction is self-sustaining, so no any holder and outer tube are necessary. The device is not fragile, it is slightly flexible, but it does not suffer plastic deformation in normal use. Quick movement in the viscose phantom liquid will result in a small bending, which disappear after stopping. This effect can be decreased by applying a rigid support in some distance from the tip. The inner part of the probe is empty; the jelly of the phantom penetrates into this hole. Fig. 2. shows the tip of the probe. The two resistive leads form attenuating transmission lines, which smooth the ripples of the voltage on the diode, and serve the time average value to the amplifier connected to the other end. The characteristic attenuation length of the transmission line is

$$\alpha^{-1} \simeq \sqrt{\omega r c} \tag{2}$$

where r and c are the resistance and capacitance of the transmission line per unit length. In the actual case $r \simeq 3.8k\Omega/mm$, $c \simeq 5\ fF/mm$; consequently $\alpha^{-1} \simeq 3\ mm$ at 900 MHz.

Obviously the resistive lines act also as antennas. They dissipative character strongly decreases this effect, but the portion closest to the dipole always will add surplus signal to the diode. If the resistive lines are orthogonal to the dipole, their geometry and resistance are identical and the change of the field strength on the distance of the two lines is negligible then this surplus voltage is mostly common-mode signal, which has no effect on the receiving characteristics. The basic problem is that the dipole antennas are not orthogonal to the resistive lines and therefore they differ in length, consequently the arrangement will supply differential-mode signal to the diode. In principle this effect could be compensate by changing the tilting angle from 54.74°, but because the effective length of the resistive line is frequency dependent the isotropy of the probe would be also frequency dependent. Therefore small SMD resistors (3.3 $M\Omega$) placed perpendicular to the dipoles are inserted between the resistive lines and the dipole. This minimises the asymmetry arising from the different length of the resistive lines. In other words, using the distributed circuit terminology, the two 2

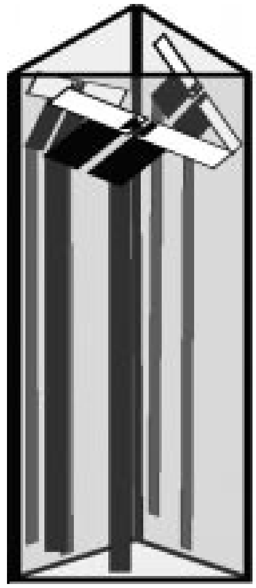

Fig. 2. The screen printed probe. The LID encapsulated detector diode is mounted into the gap of the silver printed dipole. The carbon printed resistive lines are connested to the wings of the dipole via chip resistors.

mm long chip resistor represent a transmission line with a characteristic attenuation length of about 0.15 mm at 900 MHz, which suppresses any antenna signal from the long resistive leads by a factor of 10^{-6}.

In an early work G. Smith [16] treated the receiving characteristics of an electrically short dipole antenna mounted perpendicular to a resistive transmission line. It was pointed out that the transmission line has a small contribution to the reception pattern of the dipole even in this very symmetric arrangement. The main effect is the shift of the nulls in the pattern. It has been pointed out [15] that for these probes the magnitude of all RF signals feed to the detector diode by the transmission line formed from the two chip resistors is less than 1% of the signal of the dipole. The shift of the nulls in the field pattern of the dipole will be also about $8 \cdot 10^{-3}$ in radians, i.e. in the order of $0.5°$. Immersing the probe into the phantom material, the capacitance between the components will increase proportional with the great dielectric constant of the jelly, which approaches the construction further to the ideal.

LID encapsulated zero-bias detector diodes were mounted in the gap of the dipoles. The detector diodes were preselected according their logarithmic I-V characteristics and arranged in groups containing three most uniform diodes for each probe. At low fields the detector diodes are working in the square low regime, so the output signal is proportional with the square of the voltage appearing on potential barrier $V^2 \simeq (h \times E)^2$. This rule is valid if $V << kT/q$. At greater fields the sensitivity decreases, but it still remains monotonic.

Fig. 3. shows the measured output voltages in the function of the magnitude of the square of the field for the investigated four probes. The outputs of three detectors were amplified by a factor of 200 by operation amplifiers having extra low bias currents (0.1 pA). The sum of the three outputs was measured. The probe-amplifier system has an integrating time constant of 90 ms, for decreasing the noise arising mainly from the resistors and the disturbing 50 Hz scatter from the mains. This filtering suppress the Johnson noise in the microvolt range, however the most of the noise is the $1/f$ noise of the granulated carbon prints. The experienced noise levels at the output of the amplifier differ from probe to probe, they vary in the 1-5 mV range. It should be noted here, that the preamplifier had to be shielded in these measurements. The fact is that the metallization on the PC board act for antennas and the first stage CMOS transistors have a small detectivity even at 900 MHz.

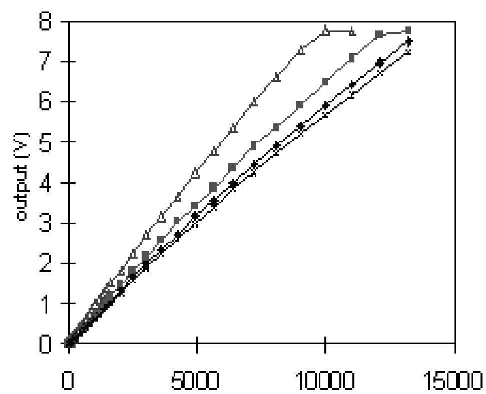

Fig. 3. The measured amplifier outputs of four 7 mm width probes in the function of the E^2 $(V/m)^2$ at 900 MHz in air. The amplifier starts to saturate at 7 V.

The absolute values of the sensitivities vary from probe to probe ±20 % according to the characteristics of the diodes built in. The linear regression analysis of the curves result in a standard deviation from the linear of about 8 % if the output voltage is less than 7 V. The dynamic range of the detection is determined by the ratio of the upper limit of linearity and the double of the noise floor (minimum signal). This value is about three great of orders (greater than 30 dB in E^2) with this accuracy. At lower fields the linearity is better, e.g. up to 1 V output (5 mV on the diode) the standard deviation is better than 0.5 % for each device. The sensitivity of the 4.5 mm wide probe is about the half.

It should be noted here that the safe dynamic range of the devices is smaller in the applications. Namely these measurements were performed in the position 2. (see below), where all the three dipoles are exposed to the same magnitude of field. In real applications the polarisation of the field is not known, so the worst case is that it is parallel to one dipole. In this case the output arises from one diode only and its deviation from the square-low regime will be greater. The method described by Schmid et al. [17] and Kanda [18] eliminates this inaccuracy. They calibrate and measure the three detectors separately and make proper corrections before summing. In this way the dynamic range of the measurement can be increased in principle without limitations.

The measurements of pulsed, or modulated signals (e.g. the GSM signal is pulse modulated with 1/8 duty circle) put also a limit to the applicable dynamic range. Due to the great filtering time constant the output is the time average of the detected signal, which can be over the square-low regime. The measurement of the three detectors separately can help in this case too, but then the calibration should be made also by similar modulated fields. In the worst case the two effects can decrease the dynamic range of GSM signal detection to 15-18 dB. This fact does not set strong limit to the applications, because in laboratories the regulation of the applied power is an obvious way for increasing the dynamic range of the measurement.

The frequency response of the probes are shown in Fig. 4. The variation of the sensitivity is not understood yet, however the total variation is about 13 % in the frequency range of $0.5 \ldots 2.0$ GHz. Below 300 MHz the sensitivity decreases drastically.

The SAR sensitivity in the 1800 MHz phantom is about the half of that measured in the 900 MHz liquid. The reason is the higher conductivity of the 1800 MHz material. The other parameters, including the probe sensitivity do not change drastically. As it can be seen from (1) the SAR value is proportional with σ, so approximately the same SAR value is occurred by half so great E^2 in the 1800 MHz liquid. The absolute sensitivity is more than enough for dosimetry. Even if the absorbed power is in the range 1-2 W/kg the detectors are in the saturation regime. Therefore it is advisable to make the dosimetric investigations with attenuated power levels. This is advantageous also from the point of thermal stability and avoiding the

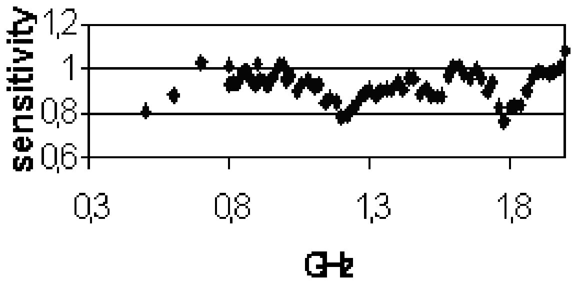

Fig. 4. The sensitivity in brain-phantom liquid has been measured at 900 MHz and at 1800 MHz. Table 4 summarises the results.

turbulence in phantom liquid occurred by the heating. The expected SAR sensitivity of the 4.5 mm probe is about the half of the above values.

Table 4. The sensitivity in phantom materials.

Phantom liquid	900 MHz	1800 MHz
Density, ρ (kg/m^2)	1279	1230
Conductivity, σ (S/m)	0.79	2.0
Relative permitivity, ε_r	41.3	44.6
SAR $sensitivity$ $mV/(W/kg)^*$	19.25	9.4

* Here the mV values regards to the voltage on the diode.

The isotropy of the probes were tested in air in an anechoic chamber. The probes were placed 3-5 m distance from the radiating horn antenna, for avoiding the near field of the source. The output of the probes was measured during the rotation of the probes around three orthogonal axes. The results are shown in Fig. 5.

The 1. position is the less informative on the probe itself, even only one working detector should give an isotropic reception. This check is characteristic mainly to the measuring conditions. A small oblateness and off-centre position can be observed, which is due the axial uncertainty of the rotation. The values of the observed average deviations are 3 % and 1.6 % for the probes No. 6 and 8 respectively, which is due to the shift of the tip of the probe less than 1 cm during the rotation. The visual inspection agrees with the greater error obtained for probe 6., because it was a slightly bent.

Revolving the device in position 2 each detector will be perpendicular to the field twice in one lap. At these positions sum of the signals from the other two detectors are measured. The non-uniform sensitivity of the detectors will result in 8 sharped deviations having three-fold symmetry.

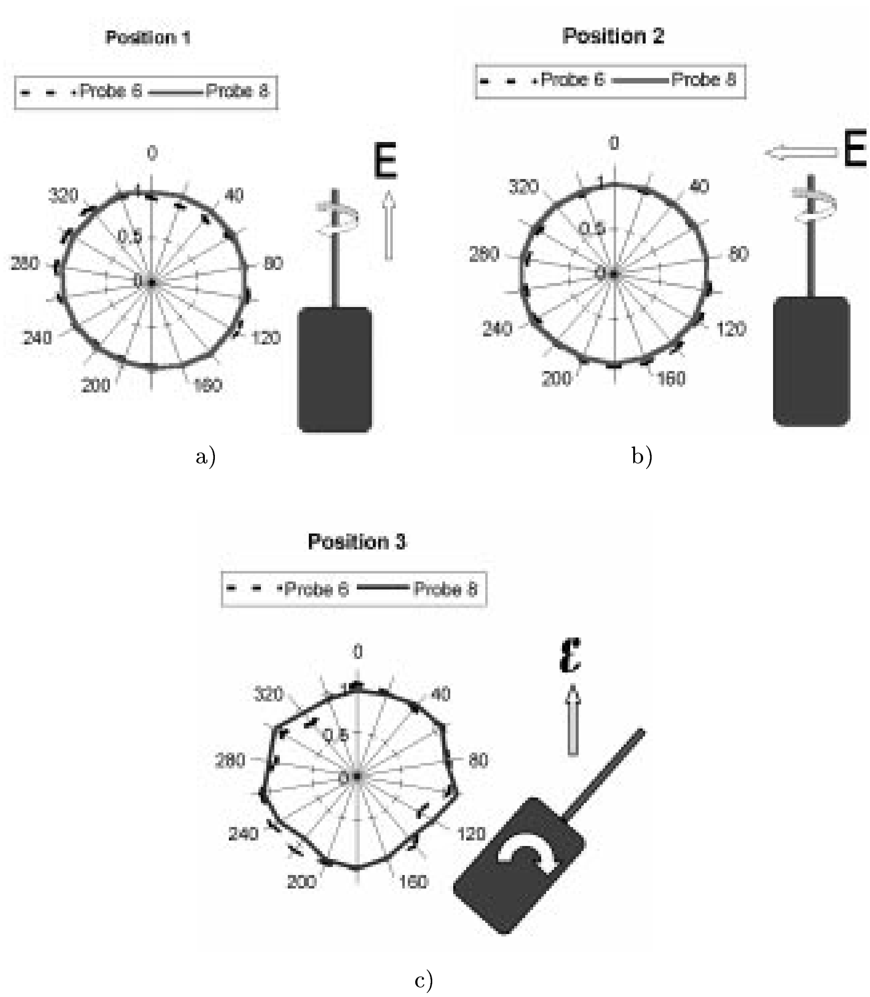

Fig. 5. The isotropy check. The measurements were made at 900 MHz, 40 V/m. The nonuniformity of the field strenght was less than 0.5 dB/cm in the place of the probe. the probes were rotated in indicated directions and the output was read in each 20 degrees. Probe 6 is the tess isotropic and probe 8 is the best in the series containing four units

Of course the deviations due to the position uncertainty described above are present in this case too, the total error is the sum of the effects. The average deviations from the ideal are 6.2 % and 2.8 % for the worst and the best probes respectively. The mentioned method of measurement [17], [18] improves the isotropy because the sensitivity differences among the three detectors can be numerically taken into consideration.

The ideality in position 3 is the most critical. Here appear both the above effects plus the receiving of the resistive transmission line. The latter should cause an 8-sharped curve with a symmetry axis tilting 54.74° to the vertical. The artefacts are also greater; namely the position of the amplifier is changing from behind to before relative the probe tip during the rotation causing the scattering of the field. The measured average deviations were 7 % and 4.8 % for the probe 6 and 8 respectively. The corresponding maximum deviations from the average are 20 % and 11 %. The deviations do not show the character expected for the reception of the transmission line, they are not 8-sharped and the statistical correlation between the two curves is only 0.38, however the starting position for the rotation was the same. Therefore this scatter can be attributed to the enhanced uncertainty of the measuring method.

It should be noted here that the anisotropy increases when the probe is immersed into the phantom liquid. That is any geometric dimensions should be converted to electric lengths. As the wavelength in the phantom is 6-7 times shorter than in air, the geometrical inaccuracies will represent greater electric length.

The short dipole-diode combination is not a matched receiving antenna. Therefore it should scatter the field, leading to a systematic measurement error. The effect was investigated by approaching a second probe to the working one and monitoring the output. No significant change was observed in air and in phantom liquid even when the two probes touched each other.

7. Conclusions

There are numerous different mobile telecommunication systems. Their application especially the use of cellular mobile phones increase rapidly. Significant part of the population have this comfortable communication and sooner or later almost everybody will use it. About the half of the emitted RF power of the hand-held phones absorbs in the head of the user. This is a new effect, such type of exposure never existed before. Therefore the related health risk should be investigated. The influence of RF field on the humans can be divided to thermal and non-thermal effects. However some weak non-thermal effects were reported, there is no evidence for permanent damage. The safety recommendations regard to the thermal effects and give limits of the absorbed power. The limits are low enough, close to the minimum requirements of the safe communication with the contemporary digital mobile phones. The older analogue cellular phones and personal mobile radios have greater emission.

Because the absorbed power can not be measured directly the test methods should use simulations. Two basically different simulating methods exist: the numerical and the physical. Both of them use phantoms. Although the numerical phantoms can have better resolution their outputs need experimental verification. An isotropic E–field probe suitable for measurements in phantoms was described.

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